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A new horizontal distillation for energy saving with a diabatic rectangular column

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Abstract–Energy saving distillation using a horizontal distillation column was experimentally examined, and the improvement of the technique has been investigated by utilizing a rectangular column. The rectangular column provides larger cross-sectional area for increased throughput and larger heat transfer area for diabatic operation. The proposed technique saves about 13.6% of energy demand compared with the vertical distillation column calculated from the HYSYS simulation. The result indicates that improved capacity of feed processing is possible with the rectangular column.

Keywords: Energy Saving in Distillation, Energy-efficient Distillation, Horizontal Distillation, Diabatic Distillation

INTRODUCTION

Because circular vertical columns have been used in the distillation processes for a long time, their design and operation procedures are well developed. Field engineers are familiar with their practical implementation. However, large energy consumption is one of major drawbacks of column utilization. Various modified columns have been developed, and their performance of energy saving was examined to find highly efficient distillation columns. The development of DWC (divided wall column) was one of the efforts to reduce the high energy demand, of which the performance has commercially been proven through field implementation [1-4]. The DWC has two separate sections in the middle of the circular column to divide the feed section and side draw section. The two sections have totally different compositions. In the conventional distillation system, the mixing of feed and intermediate product lowers distillation efficiency [5,6].

Other techniques of energy-efficient distillation include the internally heat-integrated distillation [7-10], hybrid cryogenic distillation [11], solar energy utilized distillation [12], and better controlled distillation [13]. In conventional distillation, the condenser recovers the heat supplied through a reboiler, but the temperature of the recovered heat is lower than the reboiler temperature. Therefore, the recovery is not possible at the column. In the internally heat-integrated distillation, the pressure of the rectifying section is raised to increase the temperature for the internal heat integration. Diabatic distillation is another technique for elevating the distillation efficiency by reducing the temperature difference of in-tray heat transfers [14-16].

When a horizontal column is used in the distillation, the liquid flow can be manipulated by adjusting the inclination of the column. Slow liquid flow provides longer contact time between vapor and liquid. In a packed column the contact is properly made, provided that the packing is sufficiently wet. Various materials of packing are utilized in the horizontal distillation to improve the wetting [17-21]. Diabatic operation of the horizontal column helps the wetting. In the stripping section, heat supplied through the column wall makes the liquid boiled to moisturize the packing. On the other hand, column wall cooling in the rectifying section supplies the liquid on the packing surface. Instead of a conventional circular column, a rectangular column provides larger surface area for heat transfer. Unless the column operating pressure is very high, the rectangular column is better than the circular column. The thickness of column wall allows high pressure operation, but higher than standard operating pressure of 340 kPa requires high-pressure construction incurring high investment cost [22] and lowers the rate of heat transfer. Therefore, horizontal distillation is not proper for high pressure operation. The rectangular column provides not only a large wall surface area but also a large cross-sectional area to increase the throughput of products. Distillation is the continuous process of mass transfer from liquid phase to vapor phase of more volatile component and the mass transfer of less volatile component in reverse direction. The vapor-liquid mass transfer in the horizontal distillation column occurs at the wetted layer on the packing surface in vapor phase similar to the vapor-liquid mass transfer in a vertical distillation column. In the stripping section a continuous heat supply generates vapor from the liquid to provide the sufficient interface of mass transfer. Then, the heat is removed in the rectifying section to produce condensate from the vapor providing the interface. In the adiabatic vertical column the vapor is supplied at the column bottom with a reboiler, and liquid is from the top with a condenser.

In this study a rectangular horizontal distillation column is used for the separation of methanol and *n*-propanol with diabatic operation. The energy saving performance of the proposed column is experimentally examined, and the separation capacity is compared with the previous study of horizontal distillation.

EXPERIMENTAL

1. Experimental Setup

A rectangular stainless steel column was used in this experiment

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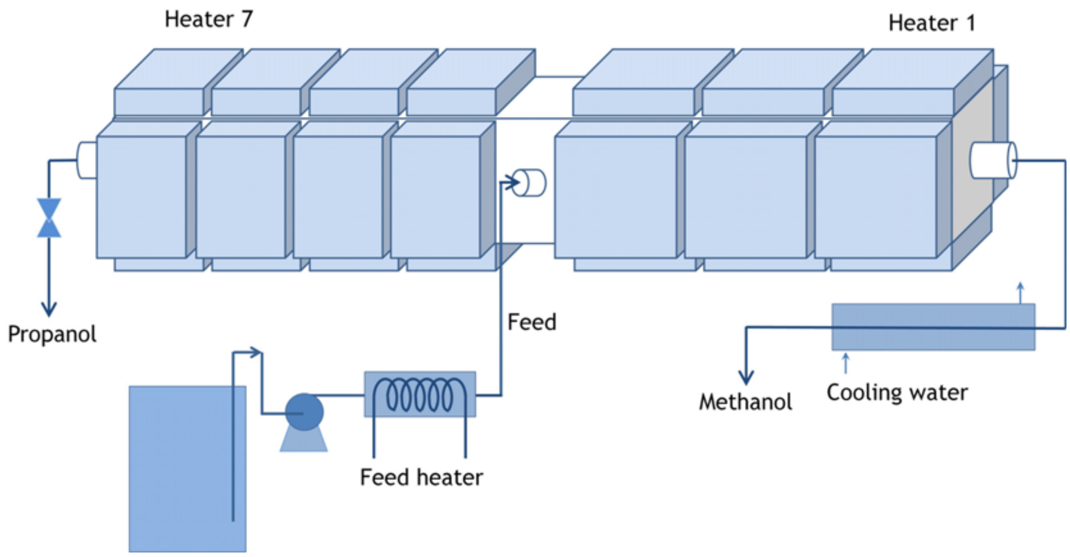

Fig. 1. Schematic diagram of experimental setup for rectangular diabatic distillation.

as described in Fig. 1. The dimensions are 3 cm wide, 6 cm high and 2 m long. The wall thickness is 2 mm. In the middle of the column a quarter inch nipple is placed for feed supply. The same size nipple placed at the left end of the column produces heavy product, and its flow rate is adjusted with a needle valve. At the right end of the column a half inch nipple is installed for the light product in vapor phase. The vapor is cooled through a water cooler to collect liquid product. Fig. 1 shows the schematic diagram of the experimental distillation column. The column was filled with 6 mm Raschig rings made of stainless steel mesh woven with 0.08 mm wire. The details of the rings are explained in Kim et al. [23]. The column was inclined 3 degrees for the lower side of heavy product production. The inclination determines the liquid flow rate to the column bottom. The inclination is also manipulated for the adjustment of liquid level at the bottom.

For diabatic operation of the distillation column, seven heating jackets are installed outside the column. The left half of the column, stripping section, has four jacket heaters of 24 cm long placed outside the column. Because the stripping section requires more heat supply, short jackets are used for more heaters installed. Three jacketed heaters of 29 cm long are placed at the right half of the column, rectifying section. The heaters are electric so that the adjustment of heat supply is simple by switching the electric current flow. The circuit of electric control is explained below. The exposed portion of the column due to the feed and products connections is insulated with sheathed glass wool to eliminate heat loss. As described in Fig. 2 the electric supply to the heating jackets is adjusted with a temperature controller. Seven separate sets of control are used for seven heaters. While the temperature controller switches the electric supply to maintain the jacket temperature at the set temperature, the amount of heat supplied is monitored from the relay signal with a PC. The computer collects the temperature and relay signal through the interface circuit. The amount of heat supply is calculated from the total time of electric connection to the heater, the summation of relay on-time.

Because the heating is mainly provided to the stripping section, more heaters are installed at the section. In conventional distillation a reboiler supplies the heat at the stripping section. At the rectifying section the column is cooled as illustrated in Fig. 3, but exposing the section to the air makes too much cooling. A small amount of heating is necessary for temperature control of the section. The heaters at the rectifying section keep the temperature steady. During the experiment the PC stores the temperatures of seven heaters and light and heavy products along with seven relay signals for later analysis of the experiment results. Feed is supplied by a metering pump, and it is preheated with a small electric heater. Table 1 lists the flow rates and composition of feed and products and temperatures of product and heaters. In addition, the amount of heat sup-

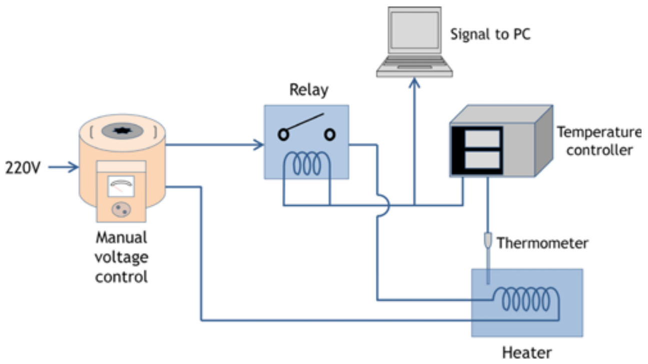

Fig. 2. Schematic diagram of electric supply and temperature and relay status measurements.

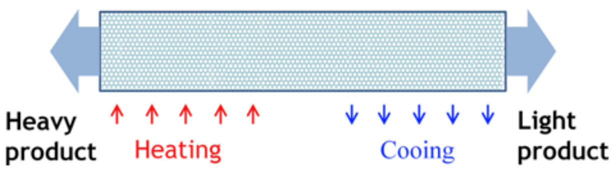

Fig. 3. Schematic diagram of heat transfer in the horizontal distillation column.

Table 1. Experimental results of methanol-*n*-propanol distillation at five different operating conditions

	Run 1	Run 2	Run 3	Run 4	Run 5
Flow rate (mL/min)					
Feed	20.5	26	31	47.5	68
Light product	9.5	12.5	14.5	23	35
Heavy product	11	13.5	16.5	24.5	33
Composition (vol. frac.)					
Feed (methanol)	0.5	0.5	0.5	0.5	0.5
Light product (methanol)	0.75	0.79	0.75	0.74	0.72
Heavy product (*n*-propanol)	0.73	0.71	0.71	0.77	0.74
Temperature (°C)					
Light product	72.0	71.2	72.1	72.6	72.6
Heavy product	73.0	74.5	73.1	75.5	74.1
Column outside temperature (°C)					
Section 1	66.7	68.6	68.3	66.5	67.1
Section 2	66.1	66.5	66.8	66.7	66.8
Section 3	71.8	70.0	70.8	72.7	72.7
Section 4	80.3	73.5	76.6	79.2	78.8
Section 5	85.1	84.8	86.5	83.8	82.0
Section 6	90.7	94.5	95.3	92.5	91.7
Section 7	98.7	105.2	105.6	104.8	102.1
Heat duty (W)	563.2	604.5	593.7	605.4	550.4

ply to the column is listed at the bottom of the table. A mixture of methanol and *n*-propanol was used as feed.

2. Experimental Procedure

When all the electric connections and PC were ready, feed was supplied by using the pump until the heavy product overflowed from the product port. Then the feed supply was on hold, and heat supply was started and controlled at the differently set temperatures. The temperature setting was the lowest at the light-product port and the highest at the heavy product. In fact, the heavy side of half is the stripping section of heating, while the light side of half is the rectifying section of cooling, as shown in Fig. 3. The mild heat supply at the cooling rectifying section compensates for the heat loss at the column wall. The heating provides the vapor-liquid contact and vapor flow to the light product port by boiling liquid at the stripping section, and the cooling does the wetting of packing to provide the vapor-liquid contact at the rectifying section. The liquid flows to the heavy product port with the column inclination of 3 degrees. The feed flow rate was adjusted with the stroke control of the metering pump, and that of heavy product was done with a valve in the product line. The flow rate of light product was not controlled to maintain the column pressure low and steady. The experiment was conducted until the steady state was maintained for more than an hour. The sample of products was taken during the experiment, and the compositions of feed and two products were measured with a gas chromatograph (Agilent Model 5892A, U. S. A.).

RESULTS AND DISCUSSION

Horizontal distillation using a rectangular column with external heating was carried out for the separation of a mixture of methanol and *n*-propanol, and the following results were obtained and discussed with the result of previous study.

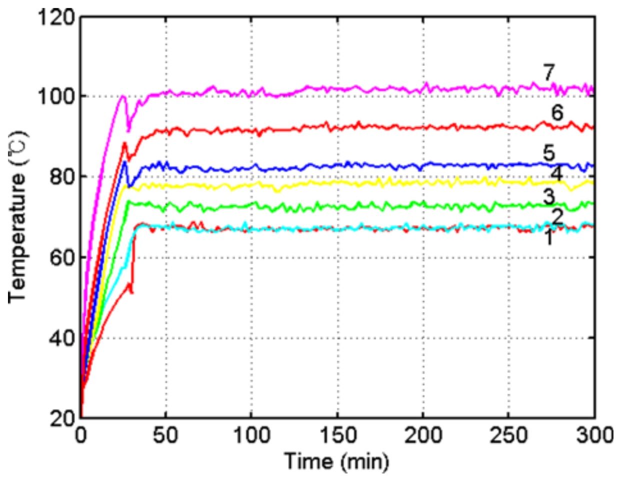

Fig. 4. Temperature variation of seven heaters for diabatic operation.

1. Experimental Results

In the preliminary experiment the distribution of temperatures along the column length was examined for the best performance of separation. A typical temperature distribution of seven heaters is displayed in Fig. 4. The curve numbers indicate the location of heaters starting from the one near to the light product port as shown in Fig. 1. The three heaters at the rectifying section work for cooling, and therefore their temperatures are lower or close to the temperature of light product as demonstrated in Fig. 5. The three heaters in the rectifying section adjust the column temperature for the even distribution of temperature through the column. Therefore the heat-

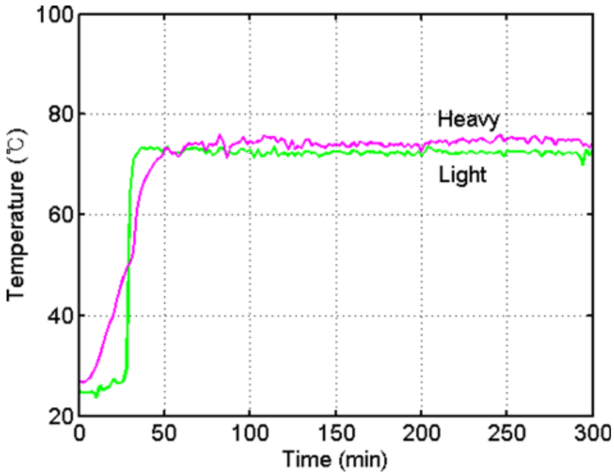

Fig. 5. Variation of product temperatures. Tube outside placement of thermometer for heavy product gives lower temperature than the real product temperature.

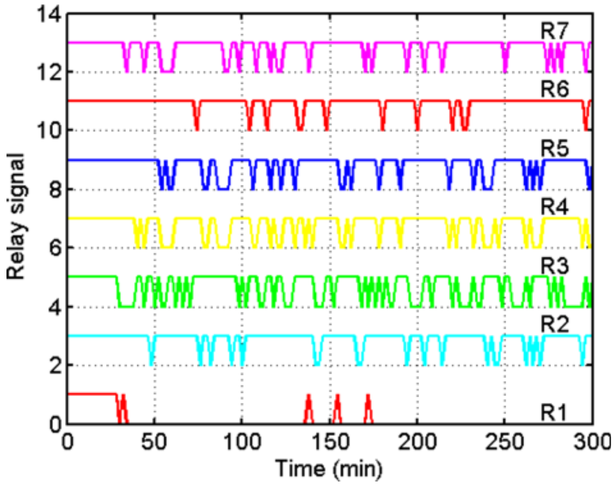

Fig. 6. Variation of relay signals. Odd numbers indicate the relay connection, and even numbers are of open relays. R1 is near to light product port, and R7 is to heavy product port.

ers control heat release through the column wall, which compensates for too much cooling through the wall. The temperatures are above the room temperature, and therefore there is cooling at the rectifying section. The relays signal for the electric supply to the heaters is shown in Fig. 6. The signals of odd numbers indicate relay on and even numbers do relay off. The relay of heater 1 shows no electric supply except the startup period, which explains that the cooling occurs in the rectifying section. The temperature increase in heater 7, the fastest, and the slowest in heater 1 during startup come from the flow of heated vapor generated at the stripping section. While the hot vapor from the end of stripping section flows to the other end, the column temperature is raised sequentially. The orderly increase of temperature in the first 30 minutes explains the vapor flow. The sudden drop of temperature after the initial rise was due to the introduction of feed, and thereafter all the temperatures were almost steady during the steady state operation.

The temperatures of light and heavy products are shown in Fig. 5. The temperature of light product was measured at the product port attached to the column, which was the vapor temperature going into the condenser. The temperature was higher than the vapor temperature of the light product, because there was a stage of vapor-liquid equilibrium at the condenser. The temperature of heavy product was measured outside the production tube, which was lower than the liquid temperature. The small difference of heavy and light product temperatures is due to the difference of measurement position, but the temperatures are helpful indicators for the control of product specification. The measured composition of products indicates that the column operation was adequate for the separation.

Table 1 lists the operating condition of five experimental runs. Feed and products flow rates and compositions are listed, and temperatures of products and column wall of seven sections are included. Though different amounts of feed were supplied, the product compositions were not much changed by adjusting the column operating temperatures. In an adiabatic operation of distillation column the temperatures at the top and bottom of the column are adjusted for the product compositions. In diabatic operation of this study, the distribution of temperature throughout the column is more important than the two end temperatures. At the run 2 relatively even temperature difference between the sections of heaters within the rectifying and stripping sections separately is related to the high composition of the light product. The experimental results indicate that the horizontal distillation column can process the feed at different operating conditions for the steady product composition. The product composition is not so high, considering the large difference of boiling points of methanol and *n*-propanol, which implies that the distillation efficiency of the packing is poor. The packing has been developed for the use in vertical distillation column. The flow pattern in the vertical column is quite different from the horizontal column, and therefore a new packing has to be developed for the horizontal distillation column [24].

2. Energy Consumption

Because the distillation utilizes energy as separation medium, its energy demand is high and many previous studies have been conducted to reduce the demand. The proposed horizontal distillation is also targeting to lower the energy consumption. For the comparison of energy requirement, the power consumption was measured in the experiment.

The heat was intermittently supplied by the control of a temperature controller set at a given temperature. The moments of the electric connection are displayed in Fig. 6. When the relay (shown in Fig. 2) is on, its status is fed to the PC in a binary signal. Fig. 6 demonstrates the binary relay signals of seven heaters. The sequence from bottom to top is of the heaters from the light product port to the heavy. Odd numbers indicate on, and even numbers do off. In the first 50 minutes, the on signal appears more often, which explains the column heating during the startup. The bottom three are of the rectifying section, and the others are of the stripping section. The power supply to the heaters is summarized in Table 2. The on time was counted from the relay signal. Total time of experiment was 300 min. including the startup period, but the total relay count was 167 at the steady state. The PC used in this experiment collected two product temperatures, seven heater temperatures and two decoded relay signals. Therefore, the relay control was relatively

Table 2. The electric supply to the heaters for the diabatic operation of the column. On time means the step of relay contact. Total time count was 167 steps at steady state

Section	Heater	Heater resistance	Supply voltage	On time (in 167 counts)	Power (W)
Rectifying	1	44.2	31.1	3	0.4
(cooling)	2	46.3	47.7	138	40.6
	3	45.9	36.2	101	17.3
Stripping	4	44.3	50.7	118	41.0
(cooling)	5	44.3	71.9	136	95.0
	6	44.3	99.9	153	206.4
	7	45.9	109.3	140	218.2

Table 3. Comparison of heat duty supplied in this study and conventional distillation calculated from the HYSYS simulation with the same feed flow rate of 77 mol/h. Units are in watts

	Horizontal	HYSYS
Reflux ratio	-	0.08
Light product composition	0.72	0.72
Heat duty	550.4	637.2

slow. The voltage of electric supply was adjusted with the variable transformer shown in Fig. 2, and the voltage and the resistance were measured before the experiment. The voltage adjustment was based on the results of the preliminary experiment. The applied power was computed from the measurements.

For the comparison of energy consumption, the energy requirement of a reboiler in a vertical distillation column was computed using the HYSYS, and the result is given in Table 3. In the comparison between the experiment and ideal tray HYSYS simulation, a tray efficiency of 70% was applied to the simulation. The tray efficiency of 70% was adopted from references [25,26]. In the previous study of the horizontal column [18,24] the HEPT of 35 cm was experimentally calculated, and one of them used the same packing as in this study. Therefore, the column of this experiment is assumed to be six trays of the vertical column, which is equivalent to four trays in the HYSYS simulation. When the feed and product compositions are the same for the horizontal and vertical distillation columns, the horizontal column requires about 13.6% less energy. The calculated energy consumption of the vertical column does not include energy loss due to the poor insulation and practical heat transfer efficiency between the heater and column wall. Therefore, the real saving of energy demand is more than the 13.6%.

While the vertical distillation in a macro scale experiment processed a feed of 3,000 mL/min [27], a feed flow rate of 68 mL/min was processed in this study of horizontal distillation experiment. If the column cross sectional area is counted in the experiments, the throughput of this study is 22% of that of the vertical column. For the practical application of the horizontal distillation column, the throughput has to be large enough to process the required capacity. Though the diabatic operation of the horizontal column provides more interfacial area of the mass transfer between liquid and vapor than the adiabatic column, preparing a large interfacial area is an important factor for the large processing capacity [24]. The structured packing utilized in the vertical columns is not suitable for the horizontal column due to the different direction of vapor and liquid flows, and therefore new design of the packing is necessary for the horizontal column for better performance leading to the elevated capacity.

3. Rectangular and Circular Columns

A horizontal diabatic distillation was used in the separation of methanol and *n*-propanol in the previous study [24]. The difference in this study and the previous is the column shape and cross-sectional area. In the previous study a circular column of 4 cm in diameter was used, but here a column of 3 cm×6 cm was implemented. The cross sectional area of column in this study is about 1.5 times that of the previous study. The cross-sectional area of the rectangular column is larger than the circular column, when their nominal sizes are identical. In the previous study the circular column processed the feed at a flow rate of 37 mL/min, while a feed rate of 68 mL/min was processed in this study. The larger throughput is due to the increase of the cross-sectional area. For the passage of vapor a rectangular cross section is better for the contact between vapor and liquid in case of the horizontal column. The rectangular column provides square vapor path, but the circular column does a circular path. One other difference is the heat transfer area. In the diabatic operation of distillation column, the heat is supplied through the column wall. Therefore, a large heat transfer area has to be prepared for sufficient supply and removal of heat. The rectangular column provides larger area of heat transfer in its wall than the circular column for the same nominal size of columns. In the previous experiments of horizontal distillation [17,21] the operation was adiabatic, and the channeling and mal-distribution of liquid stream were prevented by using fabric packing material giving slow liquid flow. Therefore the distillation throughput was very small for large scale application. The proposed diabatic operation in this study raises the throughput much further with the packing designed for vertical distillation. For the increased amount of processing, the packing suitable for the horizontal distillation is necessary. Previous studies of horizontal distillation with circular [17-20] and rectangular columns [21] were adiabatic, and the efficiency was lower than the conventional distillation [18]. The results imply that the column geometry and direction do not affect the efficiency significantly. The diabatic operation of the horizontal distillation is responsible for the efficiency improvement.

CONCLUSIONS

Though vertical distillation columns have been used for a long time, their problem of high energy demand calls for many new techniques of energy saving distillation. By utilizing a horizontal rectangular column, the contact time between vapor and liquid was increased to raise the distillation efficiency. In addition, the diabatic operation known as a process of high thermodynamic efficiency was applied in the distillation. The performance of the proposed distillation column was examined through a separation experiment of methanol and *n*-propanol.

The energy consumption in the experiment was compared with that of the vertical distillation column for the same products from the HYSYS simulation, and the vertical diabatic distillation required 13.6% less energy. The rectangular column has larger cross-sectional area to process more feed, and provides more heat transfer area better for the diabatic operation.

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